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Constraining the axion mass through the asteroseismology of the ZZ Ceti star G117–B15A

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Abstract. We perform an asteroseismological study on the DAV star G117–B15A on the basis of a modern set of fully evolutionary DA white dwarf models that have consistent chemical profiles at the core and the envelope. We found an asteroseismological model for G117–B15A that closely reproduces its observed pulsation periods. Then, we use the most recently measured value of the rate of period change for the dominant mode of this pulsating star to impose a preliminary upper limit to the mass of the axion.

1. Introduction

Pulsating DA (H-rich atmospheres) white dwarfs, also called ZZ Ceti or DAV stars, are the most numerous class of degenerate pulsators, with over 148 members known today. They are characterized by multiperiodic brightness variations caused by spheroidal, non-radial g -modes of low degree with periods between 70 and 1500 s (Winget & Kepler, Althaus et al. 2010a). G117–B15A is the most well-studied star of this class of variables. The rate of change of its 215.2 s period is very small: $\dot{P} = (4.07 \pm 0.61) \times 10^{-15}$ s/s (Kepler 2009), with a stability comparable to that of the most stable millisecond pulsars. The *axion* is a hypothetical particle that appears as a consequence of the symmetry postulated by Peccei & Quinn (1977) to solve the strong CP (charge-parity) problem in quantum chromodynamics. Axions are considered as candidates for dark matter of the Universe, and their contribution depends on their mass (Raffelt 2007). Interestingly enough, axion emission is supposed to take place in the cores of white dwarfs (Isern et al. 1992, 2008). Since axions can freely escape from such stars, their existence would increase the cooling rate and, consequently, the rate of change of the periods as compared with the standard one. In this work we present a new asteroseismological model for G117–B15A and use the more recent measurement of the rate of change of the 215.2 s period to impose new constraints on the mass of the axion.

2. A new asteroseismological model for G117–B15A

Table 1. Characteristics of G117–B15A and of our seismological model.

Quantity	Koester & Holberg (2001)	Bergeron et al. (2004)	Our seismological model
T_{eff} [K]	$12\,010 \pm 180$	$11\,630 \pm 200$	$11\,985 \pm 200$
M_*/M_\odot	0.55 ± 0.10	0.59 ± 0.03	0.593 ± 0.007
$\log g$	7.94 ± 0.17	7.97 ± 0.05	8.00 ± 0.09
$\log(R_*/R_\odot)$	—	—	-1.882 ± 0.029
$\log(L_*/L_\odot)$	—	—	-2.497 ± 0.030
M_{He}/M_*	—	—	2.39×10^{-2}
M_{H}/M_*	—	—	$(1.25 \pm 0.7) \times 10^{-6}$
$X_{\text{C}}, X_{\text{O}}$ (center)	—	—	0.28, 0.70

We performed a detailed asteroseismological study of the DAV star G117–B15A using a grid of evolutionary models characterized by consistent chemical profiles for both the core and envelope, and covering a wide range of stellar masses, thicknesses of the hydrogen envelope and effective temperatures. This constitutes the first asteroseismological application of the DA white-dwarf models presented in Althaus et al. (2010b). These models were generated with the LPCODE evolutionary code from the ZAMS through the thermally-pulsing and mass-loss phases on the AGB and finally to the domain of planetary nebulae and white dwarfs. The effective temperature, the stellar mass and the mass of the H envelope of our DA white dwarf models vary in the ranges: $14\,000 \gtrsim T_{\text{eff}} \gtrsim 9\,000$ K, $0.525 \lesssim M_* \lesssim 0.877 M_\odot$, $-9.4 \lesssim \log(M_{\text{H}}/M_*) \lesssim -3.6$, where the ranges of the values of M_{H} are dependent on M_* . For simplicity, the mass of He has been kept fixed at the value predicted by the evolutionary computations for each sequence.

We searched for a pulsation model that best matches the pulsation periods of G117–B15A. To this end, we sought the model that minimizes a quality function defined simply as the average of the absolute differences between theoretical and observed periods: $\Phi = \Phi(M_*, M_{\text{H}}, T_{\text{eff}}) = \frac{1}{N} \sum_{i=1}^N |\Pi_k^{\text{th}} - \Pi_i^{\text{obs}}|$, where $N = 3$ is the number of the periods — 215.20 s, 270.46 s and 304.05 s (Kepler et al. 1982) — observed in G117–B15A. The theoretical periods were assessed by means of the pulsation code described in Córscico & Althaus (2006). We found a best-fit model with the characteristics shown in Table 1. The internal chemical stratification and a propagation diagram (i.e., the spatial run of the logarithm of the squared Brunt-Väisälä and Lamb frequencies) of this model are shown in Fig. 1. Each chemical transition region produces clear and distinctive features in N , which are eventually responsible for the mode-trapping properties of the model. In the core region, there are several peaks at $-\log(q) \approx 0.4 - 0.5$ (where $q \equiv 1 - M_r/M_*$) resulting from steep variations in the inner C-O profile which are caused by the occurrence of extra mixing episodes beyond the fully convective core during central helium burning. The extended bump in N^2 at $-\log(q) \approx 1 - 2$ is caused by the chemical transition of He, C and O resulting from nuclear processing in prior AGB and thermally-pulsing AGB stages. Finally, there is the He/H transition region at $-\log(q) \approx 6$, which is smoothly shaped by the action of time-dependent element diffusion.

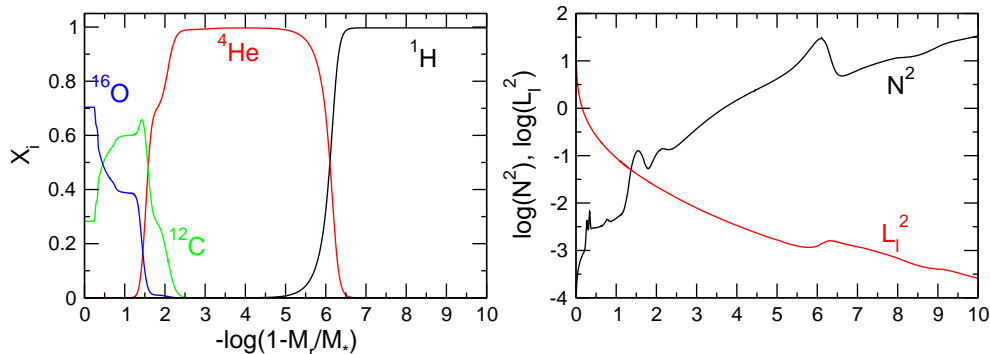


Figure 1. The internal chemical stratification (left panel) and a propagation diagram (right panel) of our asteroseismological model for G117–B15A.

3. A new upper limit for the axion mass

In order to compute the effects of axion emission, we adopted the axion emission rates of Nakagawa et al. (1988). Axion emission produces a supplementary energy loss rate to those normally considered in the standard theory of white dwarf evolution. As a result, axions accelerate the cooling process of white dwarfs. Such an acceleration of the evolution has a direct consequence on the pulsational properties of the star, because it produces a larger value of the period derivative of the oscillation modes, $\dot{\Pi} \equiv d\Pi/dt$ (Isern et al. 1992). Due to this extra cooling mechanism, the structure of the white dwarf itself is also affected but, fortunately, in such a way that for a fixed T_{eff} the pulsation periods Π are largely independent of the exact value of the axion energy losses (Córscico et al. 2001).

We have computed the values of $\dot{\Pi}$ for the modes with periods ~ 215 s, ~ 270 s and ~ 304 s ($k = 2, 3, 4$) of our asteroseismological model by adopting different axion emissions. As expected, the pulsation periods themselves do not vary appreciably, thus validating our asteroseismological model even with axion emission, but the rates of period change monotonically increase for increasing axion emission. In Fig. 2 we display the theoretical value of $\dot{\Pi}$ corresponding to the period $\Pi = 215$ s. Also shown is the most recent determination of the rate of period change for the period at $\Pi = 215$ of G117–B15A, according to Kepler (2009). Note that, if we consider a standard deviation from the observational value, we conclude that the observations are compatible with an axion mass lower than ≈ 19 meV. This value is about 5 times larger than that found by Córscico et al. (2001), but in good agreement with the range of values obtained by Bischoff-Kim et al. (2008), which derived axion masses between 12 and 26.5 meV.

4. Conclusions

On the basis of a new asteroseismological model for G117–B15A, the archetype of DAV stars, and making use of the most recent determination of the rate of period change for the dominant mode of this star, we have derived a new upper limit of the mass of the (up to now) elusive particle called *axion*. We emphasize, however, that the derived upper limit for the axion mass (≈ 19 meV) is preliminary, since we have not quantified

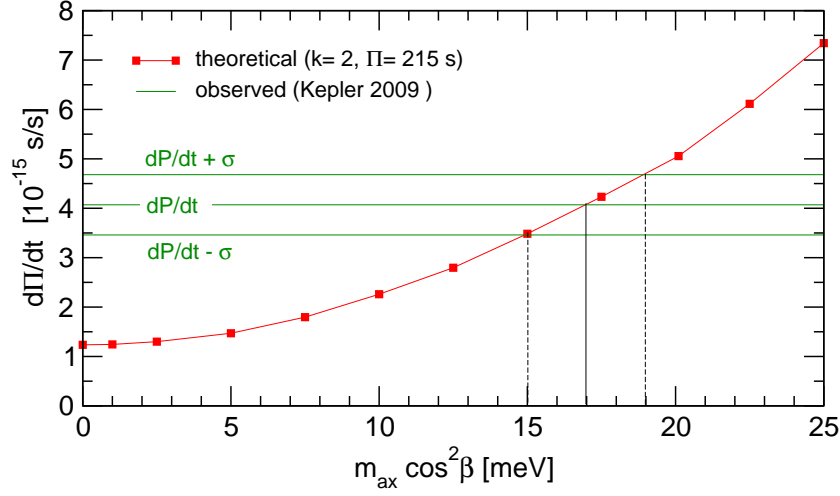


Figure 2. The temporal derivative of the period corresponding to the $l = 1$, $k = 2$ mode of our asteroseismological model in terms of the axion mass. The horizontal green lines indicate the observed value with its uncertainties (Kepler 2009).

yet the uncertainties of white dwarf modeling (core overshooting, rate of the reaction $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$) and the uncertainties related to the asteroseismological approach.

The main conclusion of this preliminary study is that, if we assume that our asteroseismological model is a good representation of G117–B15A, in order to explain the high observed value of $\dot{\Pi}(215)$ it is necessary to invoke some extra cooling mechanism, being the axion emission a very plausible one.

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